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Environmental product development: replacement of an epoxy-based coating by a polyester-based coating

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Abstract
Purpose The purpose of this study is to document and assess the environmental impacts associated with two competing powder coating solutions using current life cycle assessment (LCA) methods and available data and to check whether there is a conflict between environmental performance and occupational health issues.
Materials and methods Data have been gathered for the manufacture and application of the two different powder coatings. The case study is a cradle-to-gate study, using retrospective data. The data were entered into the SimaPro 7.2.4 LCA software and environmental impacts calculated using IPPC 2007, CML-IA and USEtox™ classification and characterisation methods. The USEtox methods were used both with and without interim factors, and this distinction was very important for the ranking of the alternatives. The study was performed using the functional unit: *Surface treatment of the "foot-cross" of one H05 5300 office chair for 15 years (the lifetime of the chair)*, where the reference flow was 172 g of powder coating to fulfil this function.

Literature about the known health effects associated with chemicals in the two solutions was also consulted in order to assess whether the main concerns driving the desire to replace the epoxy-based powder coating have been addressed and improved through using the polyester-based alternative.
Results and discussion The life cycle environmental impacts evaluated show improvements in the potential environmental impacts analysed due to the substitute polyester-based coating. The results for human toxicity and freshwater ecotoxicity potentials are dependent on the inclusion of interim characterisation factors. Literature sources provide evidence of irritation and sensitisation effects associated with epoxy resin, but not for the polyester resin alternative.
Conclusions Substitution of the epoxy-based coating by a polyester-based alternative reduces the occupational health risk for workers coming into contact with the powder coating. The results show that this substitution has also led to reduced potential environmental impacts: global warming, ozone depletion, photochemical oxidant creation, acidification, eutrophication, human toxicity and freshwater ecotoxicity, when the interim factors for some metals and organics are included in the USEtox calculations.

Keywords Case study · Furniture · Life cycle assessment · Powder coatings · USEtox

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1 Introduction

The work presented in this paper was performed as part of the Innochem research project (Hanssen 2010) financed by The Norwegian Research Council (BIA program) and the companies HÅG as and Jotun A/S. The Innochem research project is a Business Innovation Arena Project called *Innovations in response to new regulations of conventional materials in a life cycle, functional and holistic perspective*, or Innochem 2006. The project aims to turn new regulations of chemicals (REACH, Commission of the European Communities 2007) into a promoter of innovation instead of being a threat to R&D, innovation and production of chemicals in Norway and Europe.

This paper presents a case study performed for HÅG, where two alternative coatings were analysed using life

cycle assessment (LCA). HÅG is part of Scandinavian Business Seating AS, producing seating solutions for the international business furniture market.

2 Background: two alternative coatings

The coating HÅG uses for the "foot cross" part of its office chair, shown in Fig. 1, must give the appearance of polished metal, but not contain environmentally harmful substances, e.g. chrome. The coating must be robust and scratch-resistant; otherwise, it will begin to look worn before the rest of the chair has come to the end of its normal 15-year life. If a customer replaced a chair early because of this, the environmental impacts associated with the customer's chairs would increase (more resource use, production activities, etc.) and HÅG's image as a high-quality design company would be damaged.

Some of HÅG's customers have specified a requirement for purchasing, stating that products purchased cannot contain epoxy. Thus, HÅG asked its coating supplier to provide an alternative to the epoxy-based powder coating that was previously used. This alternative was a polyester-based powder coating. It was not clear to HÅG whether this purchasing requirement was based on fact; it is possible that a general feeling against epoxy could have arisen from press coverage, rather than from a sound scientific basis. In order to provide a factual basis for choice, Ostfold Research documented the life cycle environmental profile of the epoxy-based powder coating compared to the polyester-based alternative, as part of the Innochem project.

Fig. 1 HÅG's H05 5300 chair, illustrating the metal "foot cross"

HÅG has a rigorous environmental policy (HÅG 2010), which requires that they produce chairs with a long life, that are made of durable and "environmentally friendly materials". They also state in their environmental policy that they want to be able to guarantee to their users that their products do not emit harmful gases or substances. The powder coating used should not leave harmful residues that will come into contact with the consumer. The process of applying the epoxy coating was enclosed, and the heat treatment of the foot-cross ensured that the coating was melted and cured and hence in an inactive form. However, there is some evidence that epoxy can be harmful for workers (West System Inc. 2008).

There is factual evidence about sensitisation of workers to epoxy (System Three 2008; Gamer et al. 2008; Crepy et al. 2006; Peristianis et al. 1988), but HÅG has not experienced any occupational health issues with this substance at their factory in Røros, Norway (Hæskje 2008, personal communication). HÅG's powder coating process is a closed process. Worker exposure would normally occur only to the workers involved in opening the sacks of powder coating before it is charged into the silo. The powder coating is applied in a closed spray chamber, under vacuum, ensuring no further worker exposure. The workers in contact with the sacks of powder coating wear protective equipment (a fine particle filter mask, safety glasses and gloves). The powder coating process has been described as being the same for both types of powder coating used (Haugen 2008, personal communication). It should also be noted that the epoxy raw material for the Jotun powder coating used by HÅG was in solid form and had a molecular weight of >1,200 g/mol. Epoxy products are often split into ranges, according to molecular weight. Epoxy products with molecular weights lower than 1,000 g/mol are classified as having a high risk for sensitisation. Tavakoli (2003) carried out a literature review and industry survey of the skin sensitisation effects associated with epoxy resins. This study found that lower molecular weight epoxy resin (e.g. 340 g/mol) is mainly responsible for epoxy allergy and recommends the use of higher (>900 g/mol) molecular weight epoxy resins to reduce or prevent the possibility of developing an allergy.

3 Materials and methods

The work presented in this paper is concerned with two different types of effects, defined here as direct (occupational exposure) health effects and indirect effects on

human health and the environment. These indirect effects arise as a result of emissions and resource consumption required for manufacture and use of the powder coating product. The direct health effects (for workers exposed to the powder coating product) are considered by consulting available literature, whereas the indirect effects are assessed using LCA and calculating results for the two different coating case studies. The LCA work is the main focus of this paper, but the literature search performed to ascertain whether there is evidence for the occupational health concerns is also important for HÅG. It is also of interest to see whether the change in coating can lead to a conflict between occupational health improvements and indirect environmental effects. It is possible that a trade-off situation could arise, where the improvement of one aspect, such as health effects associated with a product, could result in a worsening of other effects, such as climate change impacts.

3.1 LCA methodology

3.1.1 Goal definition

The goal of the LCA was to compare two products that HÅG could use to coat metal parts; documenting the change that occurred when HÅG switched from the epoxy-based powder coating to the polyester-based powder coating they currently use. The intended audience for the detailed information available from the study was HÅG and Jotun (the coatings manufacturer, which has supplied HÅG with both coatings). The LCA presented here was also performed as part of a PhD study. The results will be used by HÅG and Jotun to evaluate the success of their product development process. HÅG will also use the information in order to gauge whether the change to a polyester-based coating required by their customers resulted in a product improvement.

3.1.2 Scope definition

The LCA approach that was used can be described as retrospective (Tillmann 2000; Ekvall et al. 2005) or attributional (European Commission 2010), and this is appropriate for Type III Environmental Declarations and Ecodesign projects (EPDs, Baumann and Tillman 2004; European Commission 2010). The term attributional is applied to LCAs performed for systems where the data used are historical. The aim of this case study was to analyse whether the change from the epoxy-based coating to the polyester-based coating had the desired improvement effect. Thus, it is a typical case where the attributional approach (Type A situation) is appropriate (European Commission 2010). The LCA methodology used for the comparison is described further in this section of the paper.

The function of the product systems and functional unit The coatings must provide adequate protection for the metal parts to ensure that they do not look shabby before the seating solution has reached the end of its 15-year functional life in an office environment. The seating solution has a powder coating on the metal parts, which the producer confirmed was the same amount by mass for both coatings. Changing from one product to another, for environmental reasons, might be expected to introduce a trade-off, where product functionality, longevity or other quality issues can be affected. However, quality control tests performed by Spencer (2010a, b) show that this is not the case for this product change. The results show that the polyester-based powder coating performs at least as well as the epoxy-based coating when exposed to wear and tear.

The powder coating producer could not produce itemised data for production of the two different powder coatings in their production facility. The allocation of environmental burdens from production between these two different powder coatings was therefore performed on a mass basis. The functional unit used for comparison of the two coatings is therefore: *Surface treatment of the "foot-cross" of one H05 5300 office chair for 15 years (the lifetime of the chair)*, where the reference flow is 172 g of powder coating to fulfil this function.

Product system and system boundaries The product system to be studied was originally a cradle-to-gate study of two seating solutions that are the same, with the exception of the coating applied to the metal parts. This is still a cradle-to-gate study, but due to the fact that the life cycles for these two seating solutions were exactly the same, except for the coatings, only the parts of the systems that were different are included in the assessment presented here. This means that the product system studied and presented here is a cradle-to-gate system for powder coatings applied to the metal foot-cross for the H05 5300 office chair.

The assessment performed was for coatings applied at HÅG's Røros factory in Norway, where the powder coatings compared are both produced by Jotun AS in Sandefjord in Norway. The raw material suppliers for Jotun are international. As the study was retrospective, data for suppliers were used from the reference year of 2009, where this was available. Section 3.1.3 contains more information about the data used as the reality of the data quality and data availability meant that database data were used extensively.

Life cycle impact assessment methods and types of impacts The impact indicators used for the seating solution's Environmental Product Declaration (EPD) in Norway (The Norwegian EPD Foundation 2008) were calculated for the two seating solution cases. The impact indicators required for an EPD do not currently include toxicity

impacts, but as toxicity and health impacts were the reason for the product development process in this case study, these were also calculated. The USEtox method was used for calculation of the potential human toxicity and freshwater ecotoxicity impacts (Rosenbaum et al. 2008; USEtox 2010). The basis and methods for calculation of the impacts included in the seating solution EPD are documented in Nereng and Modahl (2007) and have been verified according to the Norwegian EPD system requirements. These environmental impacts were calculated using the classification and characterisation methods of IPCC 2007 (global warming potential, IPCC 2007) and CML-IA (potential effects of ozone depletion, photochemical oxidant creation, acidification and eutrophication; CML 2010). These calculations were performed using the SimaPro 7.2.4 software.

USEtox is described as a consensus model for chemical impact characterisation related to human toxicity and freshwater ecotoxicity (Rosenbaum et al. 2008) and is a result of the UNEP-SETAC Life Cycle Initiative. This method is used to translate an emission into an impact by using substance-specific characterisation factors or comparative toxicity potentials. USEtox is not a complete, standalone, life cycle impact assessment (LCIA) method as it includes only human and freshwater ecotoxicity impacts, but it is a multimedia model that includes fate, exposure and effects for a number of chemical emissions. The calculations presented in this paper used SimaPro's beta version of the USEtox method, imported as a CSV file (Pré Consultants 2010, E-mail communication from Pre Software Support with file USEtox v1.01.CSV). This method included the factors available in the USEtox version downloaded from the USEtox website on May 17, 2010 and has two sets of characterisation factors that can be used for the LCA. One included interim factors (for both metals and some organic chemicals) and the other excluded these. The notes provided in the SimaPro beta version of this method imported into the software state: "Please note that metals, which all obtain interim factors, tend to dominate all the organic substances with several orders of magnitude in most LCAs" (Pré Consultants 2010, E-mail communication from Pre Software Support with file USEtox v1.01.CSV). Both sets (with and without the interim factors for metals and some organics as these heavily influence the results) were used for calculation of the results presented in this paper. Experts working with USEtox consider it important to include metals (Hauschild 2010, personal communication), even though the factors currently included in the method are interim and need more work. Although both sets of results are presented in this paper, most weight is given to the USEtox results including metals, and the reasons for this are discussed (see Section 3). It should be noted that human toxicity is presented in Section 4 of this paper in CTUh, which is an abbreviation for Comparative Toxic Units, human. The principle of comparative toxic units for human and aquatic ecotoxicity is described in Rosenbaum et al. (2008); it should be noted that both the carcinogenic and noncarcinogenic effects are aggregated in the results presented in this paper.

3.1.3 Data collection and assumptions

The data for the analyses presented in this paper are based on the EPD for HÅG's H05 5300 chair (HÅG 2009), as previously described. However, as the powder coating for the foot-cross part of the chair was the focus of attention, the author attempted to gather specific, updated data for both powder coating alternatives. Jotun produces both powder coatings, although HÅG currently use only the polyester-based coating. Both Jotun and HÅG were involved in the data collection and quality assessment processes. HÅG's powder coating facility at their Rorøs factory consumed the same amount of energy and powder coating (in weight) regardless of which type of powder coating was used (Fjerdingen 2009, 2010, personal communication; Hæskje 2008, personal communication). Jotun supplied Ostfold Research with detailed information about their production process for the powder coatings and their raw materials. It was not possible for Jotun to split up their data on energy consumption and emissions according to the different powder coating products produced by their facility. Thus, the energy consumption, emissions and waste produced were allocated to the products on a mass basis (per kilogram coating product produced). Specific raw material consumption for each powder coating was supplied by Jotun. Due to difficulties in obtaining specific data from chemical suppliers, the raw material composition data from Jotun were used to help choose the most appropriate database data for the most relevant chemicals available in the SimaPro 7.2.4 software used for the analysis. This is in line with the common situation described in Baumann and Tillman (2004), where specific data can be provided only for processes operated by the supplier, while data from further upstream must be obtained from other sources. In the current case, the author tried to obtain specific data directly from Jotun's suppliers, but without success. The consequence of this is that the results for the differences between the two different coatings were very dependent on database data quality. It should be noted that the choice of database data was made in close collaboration with an expert group of Jotun employees who possessed in-depth knowledge of the two powder coatings, their raw materials and the chemistry involved. This group of company experts on the coating formulations and chemistry were the critical reviewers for the raw material data used for this LCA. No party external to

the project team, or companies involved, performed a critical review. Data for the specific chemical in its correct physical form (e.g. powder rather than liquid) were preferred. Where that was unavailable, the closest option was used (e.g. specific chemical, but LCA data that did not include the final processing stage). The majority of the database data used was for the specific chemical. Recourse to nonspecific chemical data was only necessary for about 3% by mass of the coatings' raw materials. All of the raw material data used came from the EcoInvent 2.2 database (EcoInvent 2011) implemented in SimaPro 7.2.4 by Pré Consultants.

3.2 Occupational health

The goal for the literature search on occupational health issues was to establish whether there is evidence for the occupational health concerns associated with epoxy-based powder coatings. This information was also to be used to find out whether it was possible that a trade-off situation could arise, where the improvement of direct occupational health effects associated with a product could result in a worsening of other (indirect) effects.

The ScienceDirect search engine (Elsevier 2010) was used to find literature about the known health effects of chemicals in the two competing coating solutions. Also, internet searches were carried out for relevant material safety data sheets (MSDSs) for each chemical. The literature and MSDSs found were consulted in order to assess qualitatively whether the main concerns driving the desire to replace the epoxy-based powder coating had been addressed and improved through using the polyester-based alternative. MSDSs for the specific raw materials from Jotun's suppliers were also used. Due to confidentiality issues, only the MSDSs found in the general internet search are included in the references for this paper (see "References" Section).

4 Results and discussion

4.1 LCA

The LCA analyses performed provided results for the environmental impact categories of several potential effects: global warming, ozone depletion, acidification, eutrophication, photochemical oxidant creation, freshwater ecotoxicity and human toxicity. Quantitative data are not shown in this paper for reasons of confidentiality. It was therefore more interesting to present the differences between Jotun's two products. The results of the comparison between the two coatings (i.e. the different raw materials) are presented in the spider diagram (Fig. 2). These results for the polyester-based powder coating are shown relative to the impacts for the original epoxy-based coating.

This study does not include any form of weighting, or statistical analysis of uncertainties, so the relative importance and potential significance of the differences observed between the impact categories have not been analysed. However, Fig. 2 shows that the raw material production used for the polyester-based powder coating has lower environmental impacts for all of the impact categories analysed. The magnitudes of the impacts, in comparison to those of the alternative coating, range from approximately 35% (acidification potential) to approximately 84% (ozone depletion potential). The results for USEtox vary according to whether the interim factors for metals and some organics were included in the analysis. Without the interim factors, the difference between the

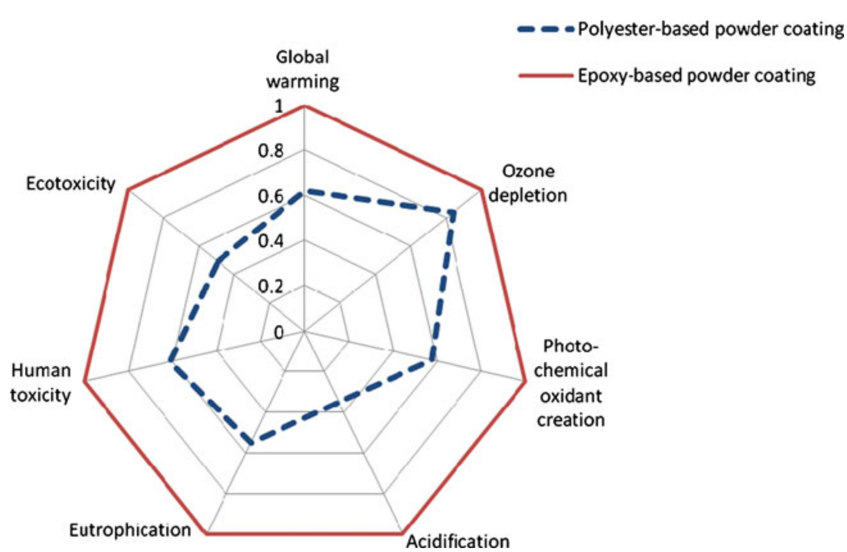

Fig. 2 Comparison of production of the raw materials for the two different powder coatings, USEtox method including interim factors for metals

two coatings changed appreciably. These results are shown in Fig. 3.

4.1.1 Global warming

For the epoxy-based coating, the main contributions to the global warming results shown are from carbon dioxide (about 93% in Fig. 2) and methane emissions to air from energy use for transport and industrial processes using fossil energy carriers. For the polyester-based system, the contributions from carbon dioxide are the most important, but dinitrogen monoxide emissions are a larger contributor (about 36%), which arise as emissions from production of chemicals.

4.1.2 Acidification

For acidification, the main contributions to the results shown in Fig. 2 are a result of the emissions of nitrous oxides, sulphur dioxide and ammonia to air from fossil energy sources and petrochemical-based raw materials for chemical production.

4.1.3 Eutrophication

Nitrogen oxide emissions to air are important for eutrophication, but emissions to water are also significant. Phosphate emissions and materials causing chemical oxygen demand are the most important emissions to water (causing 31% and 13% of the impact respectively for the epoxy-based coating and 65% and 16% for the polyester-based coating). Disposal of wastes from mining (also related to fossil energy use) is an important source of these emissions. The production and use of petroleum and gas products (both for raw material and energy purposes) are important contributors for the emissions that are most important for ozone layer depletion (e.g. Halon, CFC and HCFC emissions).

4.1.4 Photochemical ozone creation

The photochemical ozone creation potential for both systems arises mainly because of emissions of non-methane volatile organic compounds, nitrogen oxides, sulphur dioxide and carbon monoxide. For the epoxy-based system, these emissions arise from the epoxy production process, as well as fossil fuel production and use. For the polyester-based system, the most important contributing processes are organic chemical production and production and use of fossil-based energy carriers.

4.1.5 USEtox-based toxic impacts

It is possible that some readers would attach less weight to the results obtained from the USEtox method that includes “interim factors” as these may sound uncertain or flawed. However, it is recognised that data gaps that can be of importance can occur in several stages in an LCA, most notably inventory and impact assessment (Reap et al. 2008a, b). Therefore, leaving out the toxic effects of metal emissions can introduce a large data gap. The factors in the current version of USEtox consider a residence time in fresh water of no more than 1 year (USEtox™ 2010). The current USEtox model does not adequately include important mechanisms for the environmental fate of metals. Diamond et al. (2010) document the consensus about the need to incorporate bioavailability, speciation, size fractions and dissolution rates of metal complexes in the fate factor calculation part of the USEtox model. The bioavailability of

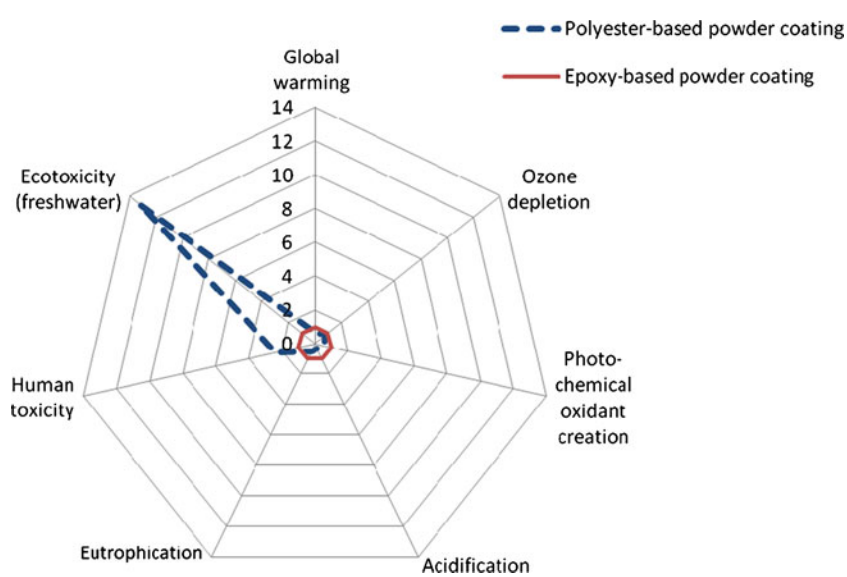

Fig. 3 Comparison of production of the raw materials for the two different powder coatings, USEtox method not including interim factors for metals

metals can be highly influenced by transformations that they can undergo in the environment; Gandhi et al. (2011) show the importance of differences in bioavailability of metals, both on a regional and local scale. If marine ecotoxicity were to be included (with its associated longer residence time), metal emissions would be likely to be even more significant for the comparative assessment presented. Experts working with USEtox consider it important to include metals (Hauschild 2010, personal communication), even though the factors currently included in the method are interim and need more work.

Considering the toxicity results without the interim factors (see Fig. 3), the USEtox human toxicity results are mostly a result of emissions of aldehydes, aromatic, volatile and chlorinated organic chemicals. Emissions to air are more important for carcinogenic effects from the epoxy-based system, whereas emissions to the water compartment are more important for the polyester-based system. For non-cancer human toxicity impacts, emissions to air dominate. For freshwater aquatic ecotoxicity, emissions to water dominate, with aromatic hydrocarbons and organic acids being the most important emissions. Production of organic chemicals contributes the most to freshwater ecotoxicity. Organic and chlorinated organic chemical production as well as production and use of energy carriers are important for potential human toxicity impacts. When the results including the interim factors for metals and some organic chemicals are included, the USEtox results change. The CTU results obtained increase by up to four orders of magnitude, and the relative importance of specific emissions changes. The potential impacts on human toxicity are dominated by disposal of residues from incineration and mining (for energy carrier production). Emissions from epoxy production are also important for the human health impacts for the epoxy system, whereas emissions from processes associated with chlorine production are of similar importance for the polyester-based system. Emissions of heavy metals to air and water dominate the contributions to potential human health impacts when the interim factors for metals are included in the USEtox assessment of both systems. The importance of heavy metal emissions for the results continues when examining the results for freshwater ecotoxicity potential for both systems. Direct emissions of heavy metals to water dominate, but deposition of heavy metals emitted to air also contributes to the potential impacts. Disposal of residues from incineration and mining (for energy carrier production) also dominate for freshwater ecotoxicity, although emissions from the burning of fossil fuels also contribute.

Excluding the interim factors for metals means that the USEtox results show a worsening in both the ecotoxicity potential and the human toxicity potential due to the change in powder coating. As previously described in the methods section of this paper (Section 3), it is desirable to include the environmental effects associated with metal emissions as far as is practicable, despite the weaknesses in the current interim factors for metals in the USEtox model. It should also be noted that prior to receiving the USEtox method beta version for SimaPro, the author performed human and ecotoxicty potential calculations using the ReCiPe method (“Europe ReCiPe H/A”, i.e. European normalisation and average weighting factors, Goedkoop et al. 2009). The results from ReCiPe were similar to those presented above (in Fig. 2) using USEtox with the interim factors for metals for ecotoxicity potential, i.e. an improvement was calculated for the polyester-based coating when compared to the epoxy-based coating. However, for human toxicity potential, the ReCiPe calculation showed approximately the same results for both coatings. The inclusion of factors for metal emissions is important for how much (if any) improvement is calculated for human toxicity potential for emissions arising from the production of alternative raw materials for the polyester-based coating. These findings are in line with the work presented in Pizzol et al. (2011) and Gloria et al. (2010) where the authors present examples and discuss the importance of characterisation factors for metals. Pizzol et al. examine nine different LCIA methods for human toxicity potential calculations, including ReCiPe and USEtox, concluding that “USEtox is recommended as the best model for LCIA on human toxicity, but mainly because of the large consensus behind it, because its uncertainties regarding metals are still high.”

4.1.6 Uncertainty and sensitivity check

As mentioned above, this study does not include any form of weighting or statistical analysis of uncertainties. However, a qualitative discussion of aspects that could potentially change the conclusions of this study is included here. Annex E in the ILCD handbook (European Commission 2010) gives a comprehensive overview of the types and sources of uncertainty in LCA, as applies to any LCA study. This section of the paper will elaborate on some issues that are specific to this study.

A sensitivity check has been performed for two significant choices for this study (European Commission 2010). These significant choices are that the two coatings are equivalent in terms of function and amount applied for the given lifetime of the seating solution (15 years). When considering the results in Fig. 2, it can be seen that the solutions would be equivalent if the polyester coating needed to be applied more often (had a shorter lifetime), or a larger amount was required. The change in lifetime or powder mass to give solution equivalence depends on the environmental impact category. For this exercise, the impact categories ozone depletion and acidification potential are

considered as these are the impacts that have the smallest and largest differences between the two coatings, respectively. In terms of coating lifetime, if the coating functions for only 12 years, rather than 15, then the difference between the two coatings is the same for ozone depletion potential, whereas the lifetime of the coating would have to be shortened to 5 years to make the two coatings equivalent for acidification potential. Similarly, increasing the polyester coating mass from 172 to 200 g (for acidification potential) or to 490 g (for ozone depletion) would give equivalence between the solutions. Ostfold Research asked both HÅG and Jotun on several occasions to confirm that in practice the same mass was used for the two coatings, and both companies did so (Fjerdingen 2009, 2010, personal communication ; Ringdal 2010, personal communication; Hæskje 2008, personal communication). There is a small specific gravity difference between the two coatings (0.1), which can imply that there could be a change in mass used. However, even if coating doses are in practice measured volumetrically, the slightly lower specific gravity of the polyester coating relative to the epoxy means that the mass of polyester coating is likely to be less, not greater. Spencer (2010a, b) also provide evidence that there is no reduced ability to withstand wear and tear as a result of the change in coating, so it is unlikely that a reduced coating lifetime is a real possibility.

The input data are not specific data for the given producers (see Section 3.1), and the uncertainty introduced by using nonspecific database data can be large. Database data have been used from the same source, as far as possible, in order to minimise the differences in errors introduced by differing system boundaries and assumptions used in different databases.

It should also be noted that the study presented here is a cradle-to-gate study and does not include end-of-life treatment of the metal parts. The chairs are included in a take-back scheme by HÅG, but if they should be disposed of in an irresponsible fashion, then further toxic impacts could occur. Releases of chemicals or fine particles during grinding of the foot-cross of the chair could be inhaled by workers (if inadequate protective equipment was used), causing health impacts and thus affecting the conclusions of this study.

As discussed above, the use (or otherwise) of interim factors in USEtox is highly significant. The differences between Figs. 2 and 3 illustrate the importance of this issue; use of interim factors changes the conclusions regarding the benefit of switching to the polyester-based coating, with respect to freshwater ecotoxicity and human toxicity.

4.2 Occupational health

Polyester resin MSDSs available for products sold internationally (e.g. Rialtech 2006) give toxicological information about polyester resin. Rialtech (2006) states that it is "not considered to cause irritant or allergic contact dermatitis based on testing results for skin irritation (rabbit), skin sensitization (guinea pig), and clinic evaluation using repeated insult patch test". By contrast, similar literature for epoxy resin (e.g. System Three 2008), gives health hazard information such as: "Acute: Slightly irritating to skin, moderately irritating to eyes. Odor may irritate nose, throat and respiratory tract of some persons. Chronic: May cause skin sensitization from prolonged and repeated contact". Here, it is seen that there is a sensitisation issue, which is not present for the polyester resin health hazard data.

The author also performed a search of relevant scientific literature about epoxy and polyester resins and their toxicity (using Elsevier's ScienceDirect search engine, Elsevier 2010). Gamer et al. (2008), Crepy et al. (2006) and Peristianis et al. (1988) show experimental evidence of the sensitisation effects that can be caused by epoxy resins and chemicals that can be present in these resins. The search for research into the toxicity of polyester resin does not produce literature of a similar nature.

The literature about the health effects of occupational exposure to epoxy and polyester, described above, shows that the sensitisation and irritation aspects associated with epoxy resin are not present for the polyester alternative. Consulting the specific MSDSs for the specific suppliers of the raw materials for the two powder coating solutions largely confirmed these findings. There are components in the polyester-based coating that "may cause sensitization by skin-contact", but these were less than 1 wt.% of the polyester-based powder coating raw materials, whereas the epoxy-based powder coating had over 60 wt.% of these. However, it should be noted that the molecular weight range of these epoxy components in Jotun's powder coating is over 1,200 g/mol (Wasvik 2010, personal communication), which is described as presenting a lower risk of sensitisation (Tavakoli 2003). Thus, the literature and safety data sheet information available leads the author to conclude that the replacement of epoxy resin in the powder coating for the foot-cross seems to have virtually eliminated the potential chronic health hazard of sensitisation and irritation for workers. Thus the substitution seems to be a success in terms of occupational health.

5 Conclusions

The occupational health concerns about the potential sensitisation and irritation effects arising from the use of an epoxy-based powder coating are supported by scientific evidence in literature. The substitution of an epoxy-based powder coating with a polyester-based powder coating is an improvement for occupational health effects as it seems to have virtually eliminated the potential chronic health hazard

of sensitisation for workers. There are components in the polyester-based coating that “may cause sensitization by skin-contact”, but these were less than 1 wt.% of the polyester-based powder coating raw materials, whereas the epoxy-based powder coating had over 60 wt.% of these.

The LCA work presented shows that substituting the epoxy-based powder coating for the polyester-based alternative reduces the potential environmental impacts analysed (global warming, ozone depletion, photochemical oxidant creation, acidification, eutrophication, ecotoxicity and human toxicity). However, the inclusion of interim factors for metals and some organics is important for how much (if any) improvement is calculated for human and freshwater ecotoxicity potential for emissions arising from the production of alternative raw materials for the polyester-based coating.

In Section 4.1.6, two specific sensitivities of the calculations are tested, relating to the durability (lifetime of the seating solution) and the mass of powder coating used. Changing to the polyester coating does not lead to overall reductions in impacts if the lifespan is reduced from 15 years to 12 years or less, or the required mass of powder increases from 172 to 200 g or more. However, there is no experimental or practical evidence either for lifespan reduction or for increased powder requirement.

The results presented in this paper suggest that the substitution of the epoxy-based powder coating with the polyester-based powder coating seems to be a success story. A product development change that was driven by a perceived benefit in workers’ occupational exposure has also reduced the potential life cycle environmental damage. Thus, concerns about reduction in environmental impacts being at odds with reduced occupational health risk are unfounded according to the present study. These issues are not contradictory in this case, but support each other.

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